



# Nitrogen and organic load removal from sanitary landfill leachates by anodic oxidation at Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and Si/BDD



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## ABSTRACT

Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and boron-doped diamond (BDD) anodes were used to study the influence of the anode material on nitrogen and organic load removal from a biologically pretreated leachate from an intermunicipal sanitary landfill: chemical oxygen demand (COD) – 6.2 g L<sup>-1</sup> and ammonium nitrogen (AN) – 0.48 g L<sup>-1</sup>. The experimental results showed that for the three anode materials under study, the COD removals were similar despite the BDD anode more easily promoting the complete combustion of the organic matter. Regarding nitrogen removal, metal oxide anodes were effective in the removal of AN, whereas BDD was more efficient in the removal of organic nitrogen. For similar experimental conditions, Ti/Pt/PbO<sub>2</sub> demonstrated the highest AN removal (90%), followed by Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> (64%) and BDD (56%). Simulated samples with analogous nitrogen content but without organic matter were also electrolyzed to better understand the elimination of the different forms of nitrogen present in the samples. At BDD anodes, ammonium is oxidized to nitrate, maintaining the nitrogen content higher than in the samples treated with the metal oxides, whereas these latter materials are more effective in the complete elimination of nitrogen, due to partial oxidation to nitrogen gas, showing that BDD is more predisposed to promote complete combustion. The anodes of metallic oxides demonstrated lower energy consumption than BDD; the energetic behavior of Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> was very similar.

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## 1. Introduction

Recently, several studies have been reported the application of advanced technologies for the treatment of sanitary landfill leachates. Landfill leachate is one of the major environmental problems concerning water pollution, and conventional treatments have been inefficient in the treatment of this type of wastewater [1–3]. Due to its effectiveness and ease of operation, the application of electrochemical oxidation to treat these effluents has been studied, with promising results. The effect of different types of anode materials and several operating factors has been assessed [4–22].

Anglada and co-workers [4–7] reported several studies concerning the electrochemical oxidation of landfill leachate using boron-doped diamond (BDD) anodes. In these studies, the effect of the applied current density, the initial concentration of chloride ions, the treatment time and the initial pH were analyzed. They reported that the electro-oxidation process of landfill leachate with BDD anodes is an efficient technology that is able to completely oxidize the organic matter and almost all ammonia under appropriate conditions. Their results showed that organic matter and ammonia oxidation are highly influenced by the applied current

density, indicating a change in the mechanism of the organic matter oxidation when high current densities are applied. Moreover, the concentration of chloride has an effect on the oxidation of ammonia, and chloride ions compete with organic matter to be oxidized at the anode. Similar conclusions were reported by Cabeza et al. [8,9] and Urtiaga et al. [21]. These authors observed that ammonium oxidation occurs at a slower rate than chemical oxygen demand (COD) decay and that chlorine evolution is enhanced at lower COD values, causing the indirect oxidation of ammonium. These authors also observed that when additional chloride ions were provided, the treatment efficiency increased.

The formation of inorganic oxidation by-products during the electrocatalytic treatment of ammonium from landfill leachates with BDD anodes was assessed by Pérez and co-workers [19]. It was found that ammonium oxidation leads to the formation of nitrogen gas and nitrate as the main oxidation products. Higher chloride concentrations have a positive influence on the formation of nitrogen as the main oxidation product. When high chloride concentrations (5–20 g L<sup>-1</sup>) were used in the presence of ammonium, chloride remained almost constant because it was regenerated during the indirect oxidation reactions.

Other studies performed with BDD anodes [14–16,20,22] confirm that the anodic oxidation can be an efficient alternative/complement to treat sanitary landfill leachates. However, despite these good results, BDD anodes present a significant

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disadvantage: they are expensive. Thus, the use of different electrode materials that are less costly than BDD for the electrochemical oxidation of sanitary landfill leachates has been reported by several authors. Cossu et al. [11] described the electrochemical oxidation of a landfill leachate with two different anode materials, Ti/PbO<sub>2</sub> and Ti/SnO<sub>2</sub>. No significant differences were found in the behaviors of the two anode materials. An average current efficiency of 30% was measured for a decrease of COD from 1200 to 150 mg L<sup>-1</sup>. The results indicated that the organic load was removed by both direct and indirect oxidation. Indirect oxidation by chlorine or hypochlorite originating from chloride oxidation was believed to be responsible for the nitrogen removal.

The indirect oxidation effect in the electrochemical oxidation treatment of landfill leachate using different anode materials was also studied by Chiang and co-workers [10]. The authors observed that the electrocatalytic behavior of the anode material strongly affects the chlorine/hypochlorite production efficiency. Moreover, there is a correlation between the COD removal efficiency and chlorine/hypochlorite production, and because COD and ammonium were removed simultaneously by the indirect oxidation effect during electrolysis, there is a competition between the removal of COD and ammonium.

Panizza et al. [17] reported the anodic oxidation of a real leachate using a lead dioxide anode. The results indicated that the organic compounds were mainly removed by indirect oxidation by the active chlorine generated from chloride oxidation.

A comparative study between different anode materials, including Ti–Ru–Sn ternary oxide, PbO<sub>2</sub> and BDD, for the electrochemical oxidation of a landfill leachate was also performed [18]. The experimental results indicated that after 8 h of electrolysis, the TiRuSnO<sub>2</sub> anode yields only 35% COD, 52% color and 65% ammonium removal. Using PbO<sub>2</sub>, ammonium and color were completely removed, but residual COD was present. On the contrary, BDD enables complete COD, color and ammonium removal and also exhibits greater current efficiency along with a significantly lower energy cost compared to the other electrodes.

Most of the PbO<sub>2</sub> and SnO<sub>2</sub> electrodes implemented in previous studies used a titanium foil substrate that may oxidize during the anodic oxidation of the leachates, leading to the formation of an insulating titanium oxides layer that inactivates the electrode [23–25]. This insulating layer may be avoided by depositing a Pt layer over the titanium foil prior to deposition of the metallic oxide [26]. The anode materials thus obtained, Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub>, have been successfully prepared and used by our research group in the electrochemical degradation of several pharmaceutical drugs [27,28]. The aim of this work was to compare the oxidation ability of these anodes with BDD anodes in the treatment of a biologically pretreated sanitary landfill leachate. To understand the elimination of the different forms of nitrogen present in the

leachate samples, assays were also performed with simulated samples without organic matter.

## 2. Experimental

### 2.1. Leachate characterization

The landfill leachate used in this study was collected from the intermunicipal sanitary landfill facility of Cova da Beira, Portugal. This site, which serves a population of over 220,000 inhabitants in 13 municipalities, has an onsite facility capable of treating up to 50 m<sup>3</sup> of leachate daily. The raw leachate was initially treated on site by an activated sludge process. The characteristics of the biologically pretreated leachate are presented in Table 1.

### 2.2. Electrodegradation experiments

Experiments were conducted in batch mode, with stirring, using 200 mL of solution. Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD were used as the anodes, and stainless steel was used as the cathode. Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> electrodes were prepared as described in the literature [26–28], and the BDD electrode was purchased from CSEM (now NeoCoat). Both the anode and cathode were used with an immersed area of 10 cm<sup>2</sup> each, with a 2.0 cm gap between them. Experiments were conducted at an applied current intensity of 0.3 A at room temperature (22–25 °C) without the addition of a background electrolyte. A Multimetrix XA 3033 unit was used as the power supply.

Simulated samples were prepared as follows: NH<sub>4</sub>NO<sub>3</sub> – 0.232 g, NH<sub>4</sub>Cl – 1.605 g, CaCl<sub>2</sub> – 0.7 g, MgCl<sub>2</sub>·6H<sub>2</sub>O – 1.42 g, NaCl – 2.472 g and KCl – 2.0986 g and distilled water up to 1 L. The reagents were analytical grade and were purchased from Sigma Aldrich and used without additional purification.

All the electrochemical assays were performed at least in triplicate. The mean values are presented for the parameters used to follow the assays.

### 2.3. Analytical methods

Degradation tests were followed by COD, biochemical oxygen demand (BOD), dissolved organic carbon (DOC), total nitrogen (TN), total Kjeldahl nitrogen (TKN) and UV–vis absorption spectrophotometry determinations, which were performed according to the standard procedures [29]. The chloride, nitrate, nitrite and ammonium concentrations were also determined by ion chromatography using a Shimadzu 10Avp HPLC apparatus coupled with a Shimadzu CDD 10Avp conductivity detector. For the Cl<sup>-</sup>, NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup> determinations, an IC I-524A Shodex (4.6 mm ID × 100 mm) anion column at 40 °C with an aqueous solution of 2.5 mM of phthalic acid and 2.3 mM of tris(hydroxymethyl)aminomethane as a mobile phase at a flow rate of 1.5 mL min<sup>-1</sup> was used. For the determination of the NH<sub>4</sub><sup>+</sup>, an IC YK-A Shodex (4.6 mm ID × 100 mm) column at 40 °C was used. The mobile phase was a 5.0 mM tartaric acid, 1.0 mM dipicolinic acid and 24 mM boric acid aqueous solution at 1.0 mL min<sup>-1</sup>.

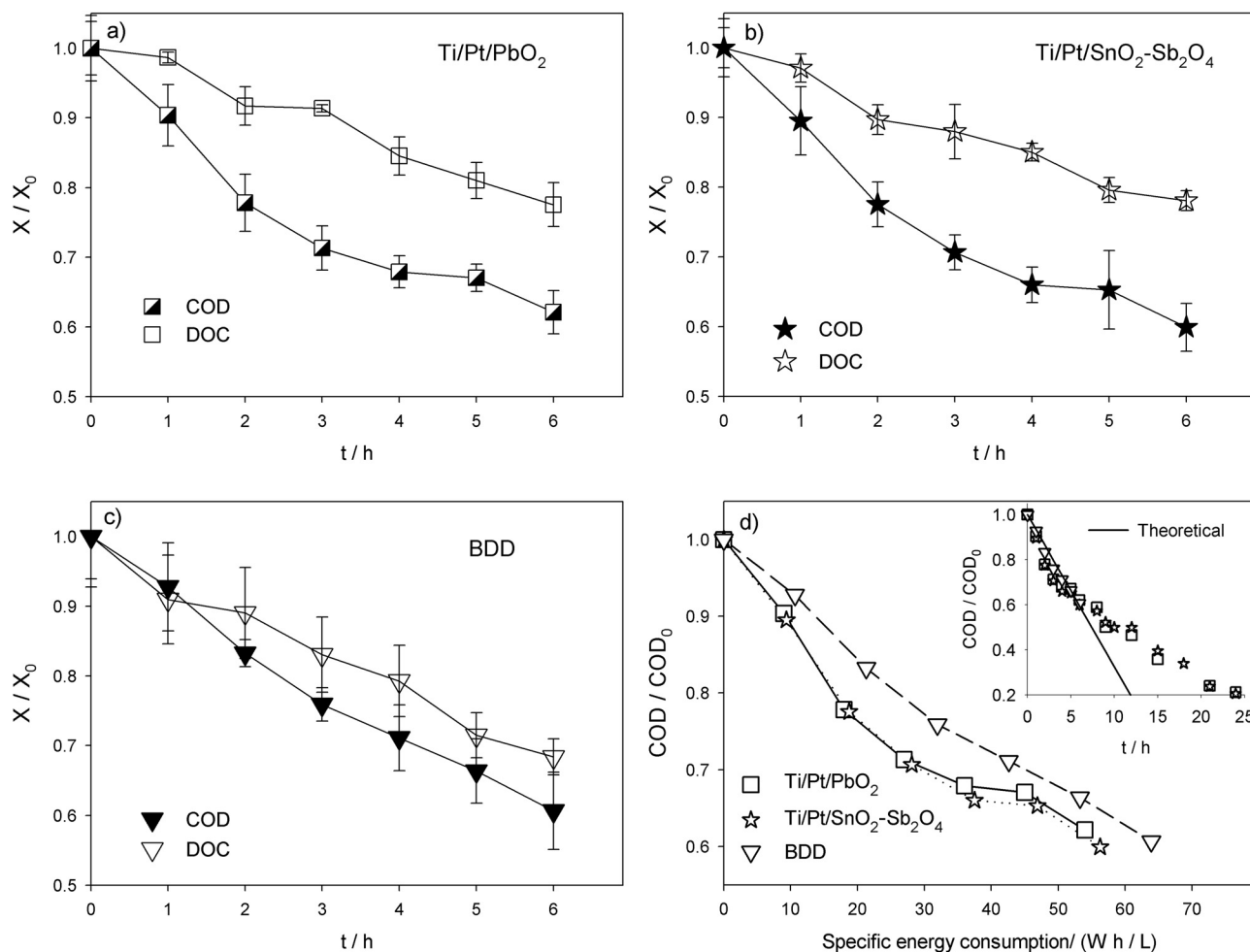
The ammonium nitrogen (AN) results were calculated based on the HPLC ammonium determinations.

COD determinations were made using the closed reflux titrimetric method. The BOD<sub>5</sub> was evaluated by determining the oxygen consumption after 5 days of incubation. The DOC and TN were measured in a Shimadzu TOC-VCPH analyzer combined with a TNM-1 unit. Before DOC and TN determinations, samples were filtered through 1.2 µm glass microfiber filters. The TKN was determined using a Kjeldatherm block-digestion-system and a Vapodest 20s distillation system, both from Gerhardt. The absorbances in the

**Table 1**  
Physicochemical characteristics of the biologically pre-treated leachate studied.

Property	Mean value (±SD) <sup>a</sup>
COD/g L <sup>-1</sup>	6.2 ± 0.4
BOD <sub>5</sub> /g L <sup>-1</sup>	0.80 ± 0.09
BOD <sub>5</sub> /COD	0.13 ± 0.02
DOC/g L <sup>-1</sup>	2.06 ± 0.02
TN/g L <sup>-1</sup>	0.82 ± 0.09
TKN/g L <sup>-1</sup>	0.78 ± 0.06
AN/g L <sup>-1</sup>	0.48 ± 0.08
Nitrate/g L <sup>-1</sup>	0.08 ± 0.01
Nitrite/g L <sup>-1</sup>	0.30 ± 0.07
Chloride/g L <sup>-1</sup>	4.7 ± 0.2
pH	9.0 ± 0.1
Conductivity/mS cm <sup>-1</sup>	22.0 ± 1.2

<sup>a</sup> SD, standard deviation.



**Fig. 1.** Variation with time of the normalized COD and DOC for the anodic oxidation experiments performed with real leachate using (a) Ti/Pt/PbO<sub>2</sub>, (b) Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and (c) BDD anodes. Variation of the normalized COD with specific energy consumption (d) and with time (inset) for the three anode materials. Error bars refer to the standard deviation of the normalized mean values.

UV-vis region were measured from 200 to 800 nm using a Shimadzu UV-1800 spectrophotometer. The pH was measured using a HANNA pH meter (HI 931400). The conductivity was determined using a Mettler Toledo conductivity meter (SevenEasy S30K).

### 3. Results and discussion

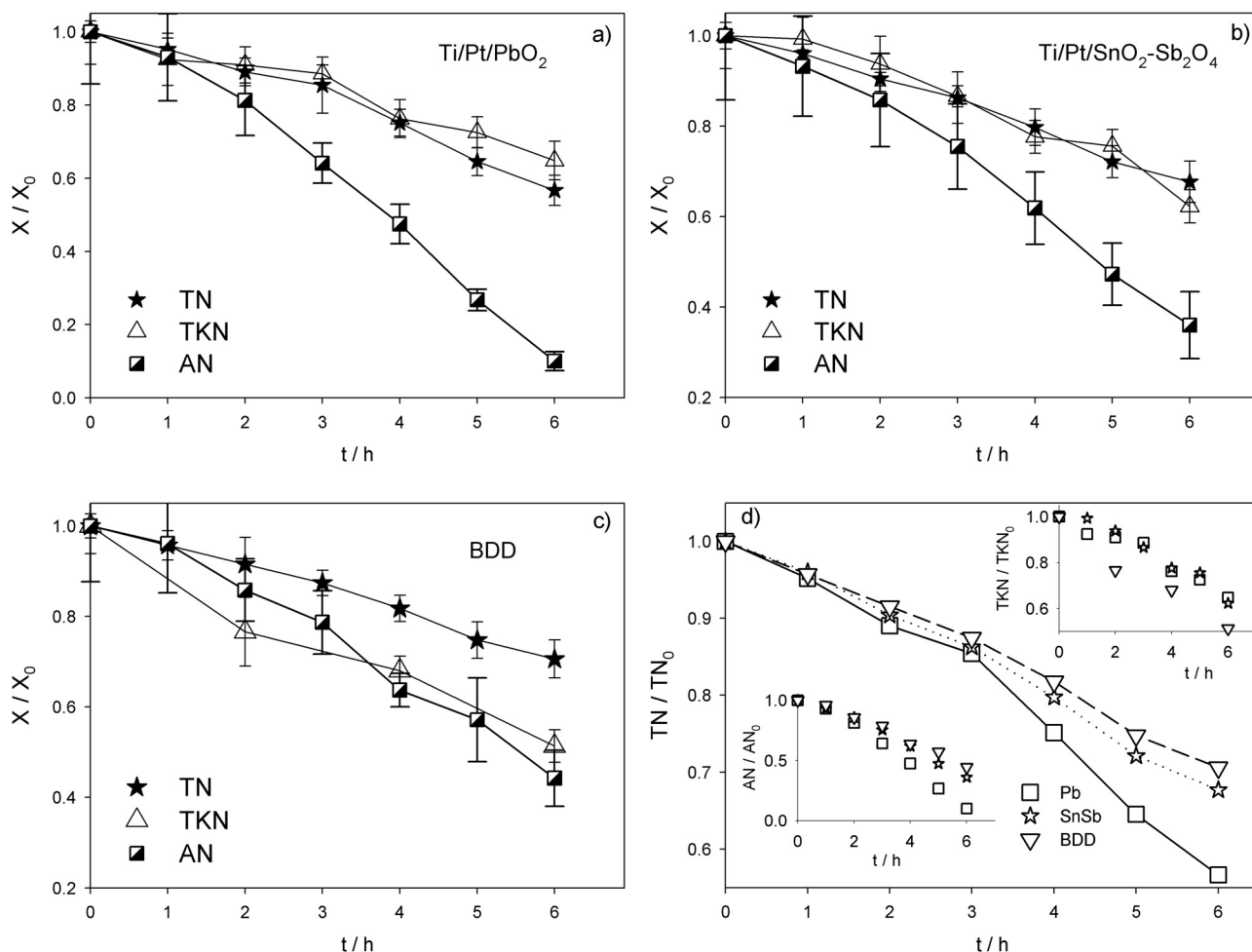
Fig. 1 presents the results for the variation with time of the normalized COD and DOC obtained from the experiments performed with real leachate and for the three anode materials used in this study. The variation of the normalized COD with electrical energy consumption is also presented. For all anodes, the DOC removal was less than that of the COD removal. This behavior has been reported previously in the literature and has been explained by the formation of low molecular mass organic compounds with high degrees of oxidation that resist further oxidation [4,14]. Despite this behavior, for the experiments with the BDD anode (Fig. 1c), the difference between the COD and DOC removal is less pronounced than for the other anodes, suggesting that the BDD anode more easily promotes the complete combustion of the organic matter. Due to the inert surface of BDD anodes, hydroxyl radicals, the main species that mediates the oxidation of the organic compounds, are very weakly adsorbed; consequently, they are very reactive toward the complete oxidation of organics. Alternatively, for Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub>, hydroxyl radicals are expected to be more strongly adsorbed on the surface; consequently, they promote the

conversion of the organic matter into more oxidized by-products rather than resulting in mineralization.

Comparing the COD evolution with time for the three anode materials studied (Fig. 1d inset), a similar type of decay was found. When these results are compared with the theoretical trend of COD during electrochemical oxidation, calculated by Eq. (1) according to the model previously proposed in the literature for electrolysis under current limited control [30], where  $I$  is the current intensity in A,  $F$  is the Faraday constant and  $V$  is the volume in m<sup>3</sup>, it can be seen that the results obtained with BDD lie over the theoretical line, whereas the results obtained at Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> are slightly better. This result is due to the electrocatalytic effect of the platinum because despite being covered by the metal oxides, platinum peaks are always detected by X-ray diffraction [27,28], probably due to the porosity of the oxide films.

$$\text{COD}(t) = \text{COD}_0 - \frac{I}{4FV}t \quad (1)$$

When the normalized COD is plotted against the electrical energy consumption (Fig. 1d) calculated based on the potential difference mean values for the assays run with each anode material, which are 6.0, 6.2 and 7.1 V for Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD, respectively, the best results are obtained for the anodes of the metallic oxides. This happens for two main reasons: the lower potential difference presented by the metal oxides for equal applied



**Fig. 2.** Variation with time of the normalized TN, TKN and AN for the anodic oxidation experiments performed with real leachate using (a) Ti/Pt/PbO<sub>2</sub>, (b) Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub>, and (c) BDD anodes. (d) Comparison of the results obtained using the three anode materials (Pb=Ti/Pt/PbO<sub>2</sub>; SnSb=Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub>). Error bars refer to the standard deviation of the normalized mean values.

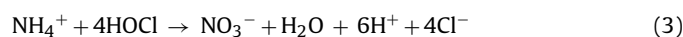
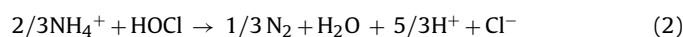
intensity because they are more conductive than BDD, and the electrocatalytic effect presented by the oxides.

Fig. 2 shows the results obtained for the nitrogen removal in the experiments performed with real leachate. Regarding the TN and TKN decays, the Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> anodes demonstrate similar behavior. AN removal is more pronounced for both materials, especially in the last hours of the assays and particularly for the assays performed with the Ti/Pt/PbO<sub>2</sub> anode.

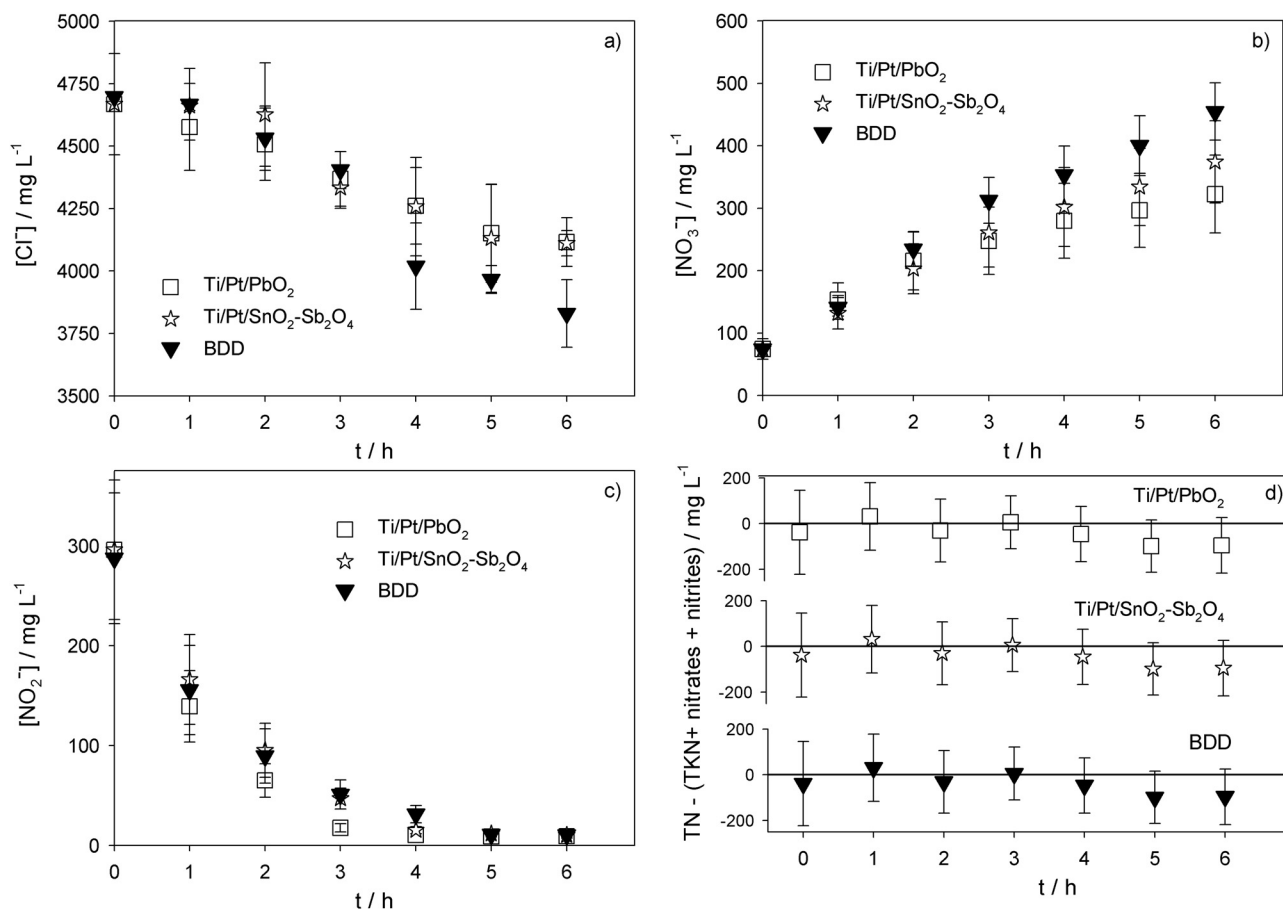
The results obtained for the experiments performed with the BDD anode (Fig. 2c) show enhanced TKN removal, but both TN and AN demonstrate reduced removal when compared with Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> (Fig. 2d and insets). At BDD, the TKN and AN decays were identical. This result indicates that BDD is more efficient in the removal of the organic nitrogen, whereas the metal oxides are mostly effective in the removal of the ammonium nitrogen. This finding agrees with the theory previously presented that hydroxyl radicals are weakly adsorbed on BDD and, consequently, they are more proficient in the oxidation of larger molecules with lower diffusion coefficients than metal oxides, which are more effective in the oxidation of smaller molecules with higher diffusion coefficients because their oxidation occurs at the electrode surface where the hydroxyl radicals are strongly adsorbed.

Comparing the COD (Fig. 1) and AN (Fig. 2) profiles during the anodic oxidation runs for Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub>, AN removal occurs at a slower rate than that of COD during the first 3 h of the assays. However, when the COD value decreases to

approximately 70% of the initial concentration, the AN removal rate increases. Similar results can be found in the literature. Cossu et al. [11], using a Ti/Pt anode, reported that the removal rate of AN was lower than that of COD at the initial stage of electro-oxidation and that AN was substantially removed in the subsequent electrochemical oxidation stage when indirect oxidation became prevalent. This increase in indirect oxidation may be enhanced by the formation of chloride-based electrogenerated oxidants, which includes HOCl [8,19]. According to Pérez et al., ammonium reacts with HOCl (Eq. (2) and (3)), regenerating chloride ions [19].



The concentration of chloride, determined by HPLC, is higher for the assays performed with Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> anodes (Fig. 3a), indicating that this ion may be involved in the oxidation of ammonium and may be regenerated after that process. Additionally, the metal oxide anodes are the most effective in removing the total nitrogen (Fig. 2d), showing that nitrogen gas is being formed at a higher rate than at the BDD anode, which is more effective at partially oxidizing ammonia to nitrate (Fig. 3b) [8]. In fact, whereas BDD anode promotes the generation of hydroxyl radicals, the high content of chloride ions induces the simultaneous formation of free chlorine, responsible for the indirect oxidation of ammonium [21], and since chlorine evolution is enhanced at lower



**Fig. 3.** Variation with time of (a)  $\text{Cl}^-$ , (b)  $\text{NO}_3^-$  and (c)  $\text{NO}_2^-$  concentrations, determined by HPLC, for the anodic oxidation experiments performed with real leachate using Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD anodes. (d) Mass balance of the different forms of nitrogen determined in solution during the assays. Error bars refer to the standard deviation of the mean values.

COD concentrations, it results in higher ammonium oxidation rates. Regarding nitrites (Fig. 3c), they are completely eliminated during the anodic oxidation at the different electrode materials.

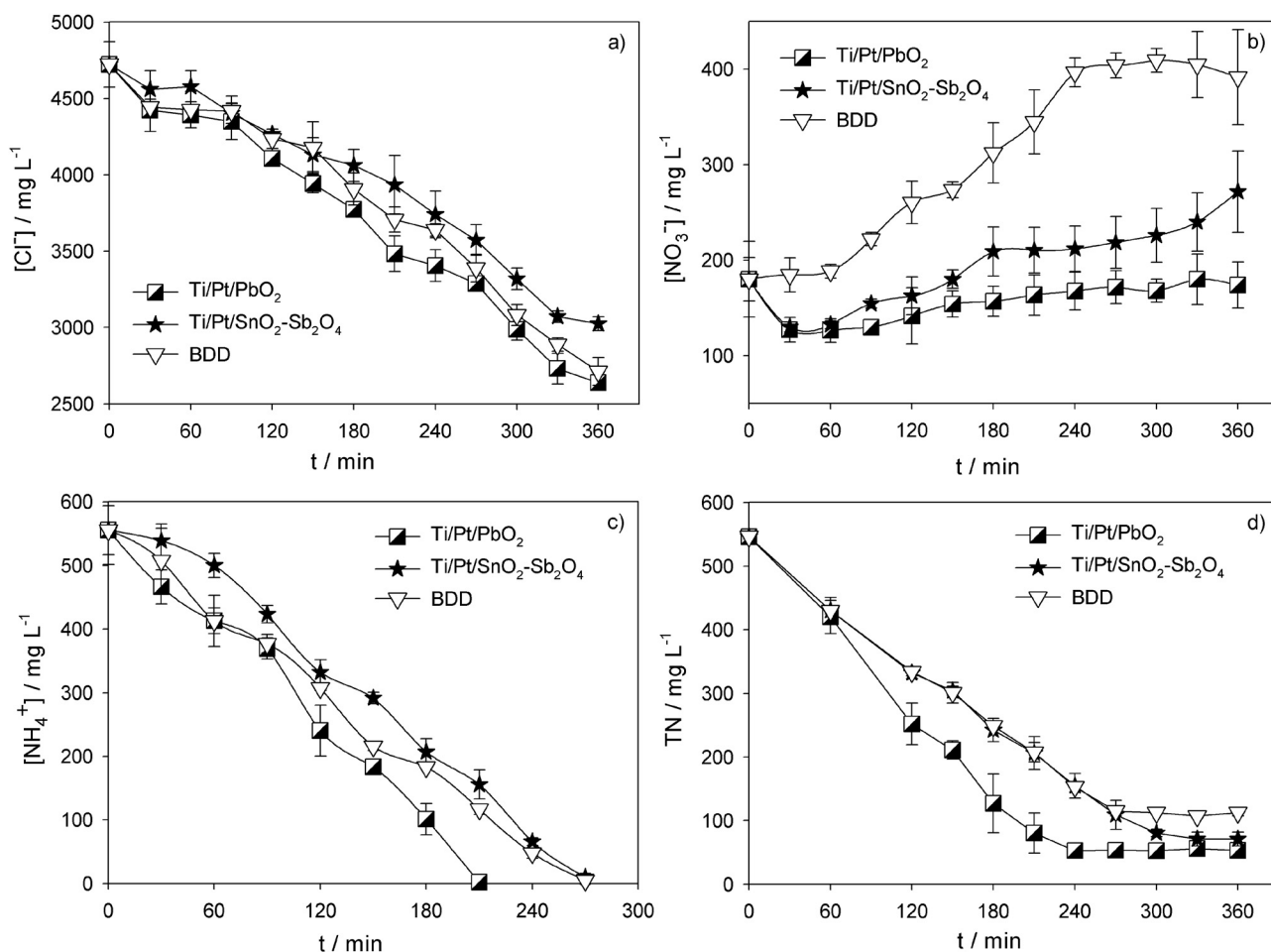
The mass balance to all nitrogen forms determined during the assays performed with the different electrode materials is presented in Fig. 3d. A discrepancy is observed only for the final period of the assays, although the value zero is always contained in the interval of the value  $\pm$  SD. This discrepancy must be related with the experimental errors of the techniques used to determine the different forms of nitrogen.

Biochemical oxygen demand after 5 days of incubation was determined for samples obtained after 6 h of electrochemical treatment with Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> anodes, and values of  $0.50 \pm 0.05$  and  $0.40 \pm 0.05 \text{ g L}^{-1}$ , respectively, were obtained. These values led to BOD<sub>5</sub>/COD ratios of  $0.13 \pm 0.02$  and  $0.11 \pm 0.02$ , respectively, indicating that the biodegradability of the samples after 6 h of anodic oxidation did not improve, and was even slightly worse in the case of the Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> anode. This issue occurs because matter that is more difficult to electrolyze is also less biodegradable and because the presence of chlorine/hypochlorite may alter the BOD<sub>5</sub> results, since these species can deactivate microorganisms responsible for the biodegradation.

After the electrochemical treatment, there were reductions of 45, 42 and 43% in the absorbance measured at 275 nm and reductions of 9.1, 8.6 and 9.5% in the conductivity for the assays performed with the Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD anodes, respectively. The reduction in the absorbance is due to the ease of degrading the aromatic structures by anodic oxidation in materials with high oxygen evolution potentials that produce high

concentrations of hydroxyl radicals [30], whereas the decrease in conductivity is due to metal deposition over the cathode caused by the cathodic reduction of the metal ions present in the leachate samples [16]. Regarding the pH variation during the assays, there was only a slight increase in the final samples of the electrolyses performed with the Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> anode (final pH of  $9.7 \pm 0.2$ ). The pH variation for the other electrode materials was within an acceptable range for experimental error.

To understand the effect of organic matter on the elimination of ammonium nitrogen, assays were run with the three electrode materials using simulated solutions containing chloride, nitrates and ammonium in concentrations similar to those encountered in the leachate samples. The results are presented in Fig. 4. The elimination rate of chloride is enhanced because there is no competition with the organic matter for oxidation. In contrast, hydroxyl radicals are free to convert ammonium, which does not participate in Eqs. (2) and (3) and which does regenerate chloride ions. The discrepancy between the nitrate formation rate for the different electrode materials increases, showing that BDD is more predisposed to oxidize ammonium to nitrates, whereas for the other materials, ammonium and total nitrogen removal are increased and nitrate formation rate is decreased, showing that the metal oxides are more effective in the complete elimination of nitrogen from solution via the partial oxidation of ammonium to nitrogen. A decrease in nitrate concentration is observed during the first 30 min of the assays performed with the oxide anodes that can be related to nitrate reduction to other nitrogen forms. This electrochemical reduction of nitrate using oxide anodes was already reported in literature [31].



**Fig. 4.** Variation with time of (a) Cl<sup>-</sup>, (b) NO<sub>3</sub><sup>-</sup>, (c) NH<sub>4</sub><sup>+</sup> and (d) TN concentrations for the anodic oxidation experiments performed with the simulated sample using Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD anodes. Error bars refer to the standard deviation of the mean values.

After the electrochemical treatment performed with this simulated solution, there were reductions in conductivity of approximately 20% for the assays performed with the different anodes, due to the oxidation of species with high conductivity, such as ammonium and chloride, and the formation of nitrate, which has a lower conductivity than ammonium. The increase in pH (from  $6.1 \pm 0.1$  to  $7.8 \pm 0.1$ ,  $7.5 \pm 0.1$  and  $6.4 \pm 0.1$  for the Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD anodes, respectively) also contributed to the decrease in conductivity.

#### 4. Conclusions

A comparative study between the oxidation ability of Ti/Pt/PbO<sub>2</sub>, Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD to remove nitrogen and organic load from biologically pretreated sanitary landfill leachates was performed, and the following conclusions can be drawn:

- The three anode materials present similar COD removal kinetics, whereas the BDD anode promotes the highest DOC removal, leading to a higher mineralization degree due to its inert surface where hydroxyl radicals, which are responsible for the indirect oxidation, are less strongly adsorbed than at the metal oxides surfaces.
- Ti/Pt/PbO<sub>2</sub> promotes the highest level of TN and AN removal, followed by Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> and BDD, whereas BDD shows the highest level of TKN removal. This effect occurs because for metallic oxides, the partial oxidation of ammonium to nitrogen gas

occurs, whereas for BDD, ammonium is oxidized to nitrate, again indicating the ability of BDD to complete oxidation.

- Metallic oxide anodes demonstrate low energy consumption because they are more conductive than BDD and also due to the electrocatalytic effect of the oxides.

Thus, Ti/Pt/PbO<sub>2</sub> and Ti/Pt/SnO<sub>2</sub>-Sb<sub>2</sub>O<sub>4</sub> are good alternatives as anode materials for the treatment of sanitary landfill leachates. The Ti/Pt/PbO<sub>2</sub> anode yields better results, mainly in terms of nitrogen removal. Although it makes the material more expensive, a Pt layer can strategically increase the electrode lifetime; the electrodes used in this work were tested for more than 1000 h.

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